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## Fine-Tuning Constraints on Supergravity Models

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### Abstract

We discuss fine-tuning constraints on supergravity models. The tightest constraints come from the experimental mass limits on two key particles: the lightest CP even Higgs boson and the gluino. We also include the lightest chargino which is relevant when universal gaugino masses are assumed. For each of these particles we show how fine-tuning increases with the experimental mass limit, for four types of supergravity model: minimal supergravity, no-scale supergravity (relaxing the universal gaugino mass assumption), D-brane models and anomaly mediated supersymmetry breaking models. Among these models, the D-brane model is less fine tuned. The experimental prospects for an early discovery of Higgs and supersymmetry at LEP and the Tevatron are discussed in this framework.

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When should physicists give up on low energy supersymmetry? The question revolves around the issue of how much fine-tuning one is prepared to tolerate. Although fine-tuning is not a well defined concept, the general notion of fine-tuning is unavoidable since it is the existence of fine-tuning in the standard model which provides the strongest motivation for low energy supersymmetry, and the widespread belief that superpartners should be found before or at the LHC. Although a precise measure of *absolute* fine-tuning is impossible, the idea of *relative fine-tuning* can be helpful in selecting certain models and regions of parameter space over others.

For example, in a recent paper two of us investigated non-universal soft parameter space and concluded that (i) lowering the high energy gluino mass  $M_3$  relative to  $M_{1,2}$  reduced fine-tuning (because fine-tuning is mostly sensitive to  $M_3$ ), (ii) having certain relations between the soft parameters at the high energy scale such as one between the up-type Higgs doublet mass and the gluino mass  $m_{H_U} \approx 2M_3$ , can reduce fine-tuning<sup>1</sup> [1]. These results follow from our observation that fine-tuning is mainly dominated by  $M_3$ , and this dominant contribution can be partly cancelled by negative contributions from other soft parameters, as can be clearly seen from the expansion of the  $Z$  mass in terms of high energy input parameters [1], for example for  $\tan \beta = 2.5$  we find

$$\begin{aligned} \frac{M_Z^2}{2} = & - .87 \mu^2(0) + 3.6 M_3^2(0) - .12 M_2^2(0) + .007 M_1^2(0) \\ & - .71 m_{H_U}^2(0) + .19 m_{H_D}^2(0) + .48 (m_Q^2(0) + m_U^2(0)) \\ & - .34 A_t(0) M_3(0) - .07 A_t(0) M_2(0) - .01 A_t(0) M_1(0) + .09 A_t^2(0) \\ & + .25 M_2(0) M_3(0) + .03 M_1(0) M_3(0) + .007 M_1(0) M_2(0) \end{aligned} \quad (1)$$

where we have implicitly assumed all the soft breaking parameters to be real, neglecting the phases<sup>2</sup>. One implication of the fact that fine-tuning is dominated by  $M_3$  is the fact that the soft scalar masses can be larger than  $M_3$  without increasing

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<sup>1</sup>Another example of how to reduce fine-tuning not mentioned in [1] is to increase  $M_2$  for fixed  $M_3$ , due to the cancellation effect.

<sup>2</sup> In the most general situation with complex soft breaking terms, the phases will enter in the subleading cross-terms in Eq. (1).

fine-tuning, a fact which has recently been emphasised in the framework of minimal supergravity in ref.[2].

In this paper we shall extend the discussion in ref.[1] in two ways. Firstly we shall study fine-tuning in various supergravity models: minimal supergravity, no-scale supergravity (relaxing the universal gaugino mass assumption), D-brane models and anomaly mediated supersymmetry breaking models (AMSB). The common feature of this class of models is that they involve a large mass scale of order the unification scale say  $M_U \sim 2 \times 10^{16}$  GeV, and supersymmetry breaking is mediated via some sort of hidden sector supergravity mechanism. Thus our analysis does not extend to either gauge-mediated supersymmetry breaking models, or models where the string scale is lowered beneath the unification scale, although it may be lowered to the unification scale. The reason why we choose these models is that they contain the largest mass hierarchy, and hence face the most severe fine-tuning constraints in general. These models also preserve the gauge unification success most simply and directly.

Secondly we focus on the key particles whose experimental mass limits lead most sensitively to increases in fine-tuning. Clearly fine-tuning is not sensitive to squark and slepton masses which can be increased substantially due to the insensitivity of the  $Z$  mass formula in Eq.1 to soft scalar masses. By contrast the lightest CP even Higgs mass is a very sensitive probe of fine-tuning, as we emphasised previously [1], and it is obvious from the foregoing discussion that the gluino mass itself is also a sensitive probe. Although we showed [1] that the chargino mass is only a sensitive probe of fine-tuning if one assumes universal gaugino masses, we shall nevertheless include it for illustrative purposes.

The implicit sensitivity of the  $Z$  mass coming from changes in  $\tan \beta$  as a result of small variations in the high energy inputs, does not appear in Eq.1. This is addressed by the master formula of Dimopoulos and Giudice [3] which yields a fine-tuning

parameter which corresponds to the fractional change in the Z mass squared per unit fractional change in the input parameter,

$$\Delta_a = abs \left( \frac{a}{M_Z^2} \frac{\partial M_Z^2}{\partial a} \right) \quad (2)$$

for each input parameter  $a$  in the model of interest. The fine-tuning is then simply the maximum value of  $\Delta_a$  over all the input parameters. Although there are many more sophisticated measures of fine-tuning available [3, 4, 5, 6], this basic measure of fine-tuning is adequate for our purposes of comparing relative fine-tunings amongst different models.

The models we consider, and the corresponding input parameters given at the unification scale, are listed below:

1. Minimal supergravity [2].

$$a_{msugra} \in \{m_0^2, M_{1/2}, A(0), B(0), \mu(0)\}, \quad (3)$$

where as usual  $m_0$ ,  $M_{1/2}$  and  $A(0)$  are the universal scalar mass, gaugino mass and trilinear coupling respectively,  $B(0)$  is the soft breaking bilinear coupling in the Higgs potential and  $\mu(0)$  is the Higgsino mass parameter.

2. No-scale supergravity [7] with non-universal gaugino masses<sup>3</sup>

$$a_{no-scale} \in \{M_1(0), M_2(0), M_3(0), B(0), \mu(0)\} \quad (4)$$

3. D-brane model [8].

$$a_{D-brane} \in \{m_{3/2}, \theta, \Theta_1, \Theta_2, \Theta_3, B(0), \mu(0)\}, \quad (5)$$

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<sup>3</sup>This is in fact a new model not previously considered in the literature, although the no-scale model with universal gaugino masses is of course well known. As in the usual no-scale model, this model has the attractive feature that flavour-changing neutral currents at low energies are very suppressed, since all the scalar masses are generated by radiative corrections, via the renormalisation group equations, which only depend on the gauge couplings which are of course flavour-independent.

where  $\theta$  and  $\Theta_i$  are the goldstino angles, with  $\Theta_1^2 + \Theta_2^2 + \Theta_3^2 = 1$ , and  $m_{3/2}$  is the gravitino mass. The gaugino masses are given by

$$\begin{aligned} M_1(0) = M_3(0) &= \sqrt{3}m_{3/2} \cos \theta \Theta_1 e^{-i\alpha_1}, \\ M_2(0) &= \sqrt{3}m_{3/2} \cos \theta \Theta_2 e^{-i\alpha_2}, \end{aligned} \quad (6)$$

and there are two types of soft scalar masses

$$\begin{aligned} m_{5152}^2 &= m_{3/2}^2 \left[ 1 - \frac{3}{2} (\sin^2 \theta + \cos^2 \theta \Theta_3^2) \right], \\ m_{51}^2 &= m_{3/2}^2 [1 - 3 \sin^2 \theta], \end{aligned} \quad (7)$$

#### 4. Anomaly mediated supersymmetry breaking [9].

$$a_{AMSB} \in \{m_{3/2}, m_0^2, B(0), \mu(0)\} \quad (8)$$

Our numerical results are based on two-loop renormalisation group running of gauge<sup>4</sup>, third generation Yukawa couplings and soft mass parameters [10]. The initial values of the Yukawa couplings are determined by the values of the third generation fermion masses<sup>5</sup>. The input soft mass parameters are then chosen in order to get electroweak symmetry breaking and the  $m_Z$  scale given by the minimisation conditions of the one-loop corrected Higgs potential [13, 14],

$$\frac{m_Z^2}{2} = \frac{m_{H_D}^2 - m_{H_U}^2 \tan \beta^2 - \Delta_Z^2}{\tan \beta^2 - 1} - \mu^2, \quad (9)$$

where  $\tan \beta = \langle H_U \rangle / \langle H_D \rangle$ ,  $\Delta_Z^2$  is the one-loop contribution, and the parameters in Eq. (9) are evaluated at  $m_Z$ . In practice, for the numerical calculations we use as input  $\tan \beta$  and  $\text{sign}(\mu)$  (we always take  $\mu > 0$ ) and obtain  $\mu(0)$  and  $B(0)$  from the minimisation conditions.

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<sup>4</sup>When running the gauge couplings we have included complete threshold effects at order 1-loop [11] and used the step-function approximation in the 2-loops coefficients.

<sup>5</sup>We have included one-loop susy threshold corrections, QCD and electroweak corrections when converting pole mass values to running mass values at the  $m_Z$  scale [12].

Our main results are shown in Figs.1-4, corresponding to SUGRA models 1-4 above. The results are shown for three values of  $\tan\beta = 2, 3, 10$ , corresponding to three sets of curves from top left to bottom right, respectively. In each case we plot the maximum sensitivity parameter  $\Delta^{max}$  as a function of particle mass, for the lightest CP even Higgs boson (short dashes), the lighter chargino (long dashes) and the gluino (solid). The lightest CP even Higgs boson is calculated using the one-loop RG-improved effective potential approach [15], which includes the leading two-loop corrections to the Higgs mass<sup>6</sup>. The gluino mass also includes the corrections due to gluon/gluino and quark/squark loops [17, 12].

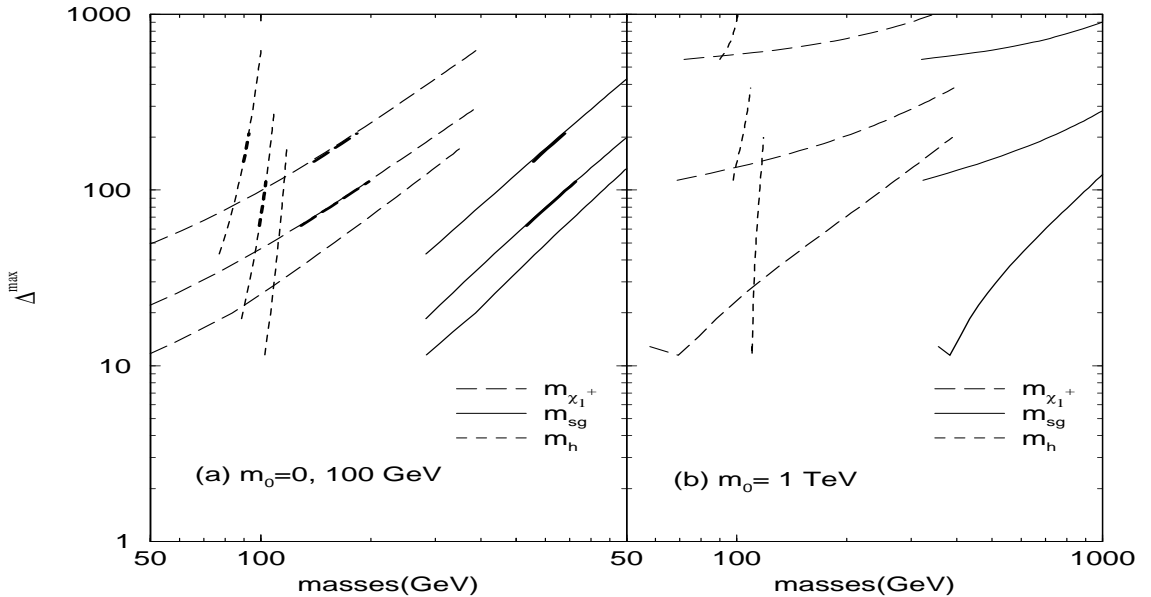


Figure 1: Results for the minimal SUGRA model. The maximum sensitivity parameter  $\Delta^{max}$  is plotted as a function of the lightest CP even Higgs mass (short dashes), gluino mass (solid line) and lightest chargino (long dashes). For each particle type, the three sets of curves correspond to  $\tan\beta=2, 3, 10$ , from top left to bottom right, respectively. In panel (a) the shorter, thicker lines correspond to  $m_0 = 0$ , while the longer lines are those for  $m_0 = 100$  GeV. In panel (b) the results correspond to  $m_0 = 1000$  GeV.

In Fig.1 we give the fine-tuning results for mSUGRA. The present LEP2 mass limits of around 100 GeV on the Higgs and chargino compete for providing the tightest

<sup>6</sup>The expected accuracy in the computed Higgs mass is estimated to be  $\sim 2$  GeV. A different approach to the calculation of the Higgs mass can be founded in Ref. [16].

fine-tuning constraint, while the current Tevatron gluino mass limit of around 250 GeV provides a slightly less severe limit. For a Higgs mass of 100 GeV,  $\tan\beta = 10$  allows fine-tuning to stay at around 10, but as the Higgs mass increases it rapidly overtakes the chargino mass in importance and as it approaches 110 GeV fine-tuning rises steeply to 100. Comparing Fig.1(a) with  $m_0 = 100$  GeV, to Fig.1(b) with  $m_0 = 1000$  GeV we see that for  $\tan\beta = 10$  the curves are very similar, as emphasised in ref.[2]. However we emphasise that for lower values of  $\tan\beta$  fine-tuning increases substantially as  $m_0$  is increased from 100 GeV to 1000 GeV in mSUGRA. Also in Fig.1(a) we show results for no-scale mSUGRA with  $m_0 = 0$  for  $\tan\beta = 2, 3$  seen as short lines almost superimposed over the  $m_0 = 100$  GeV lines. The reason why the no-scale lines are so short is that if  $M_{1/2}$  is too small the right-handed slepton falls below its experimental limit of 88 GeV, while if  $M_{1/2}$  is too large it becomes the LSP. Thus there is only a narrow allowed window for  $M_{1/2}$  which in the case of  $\tan\beta = 10$  is non-existent.

In Fig.2 we give results for a generalised version of no-scale mSUGRA hitherto not considered in the literature in which  $m_0 = 0$  as usual, but now we allow the gaugino masses to be non-universal. For definiteness we take  $M_1(0) = M_2(0)$ , but allow these gaugino masses to be different from the high energy gluino mass  $M_3(0)$ . The first point to make is that by relaxing gaugino mass universality, a larger parameter space is opened up and the constraints which forced  $M_{1/2}$  into a small allowed range in the no-scale mSUGRA model are now replaced by large allowed regions in non-universal gaugino mass space. For example taking  $M_2(0) = M_1(0) = 250$  GeV in Fig.2(a) we see a large range of  $M_3(0)$  is allowed. Also we find that fine-tuning is generally smaller in this model than mSUGRA for  $\tan\beta = 10$ . The reason is that although the Higgs curves in Fig.2(a) are very similar to those in Fig.1(a), the chargino curves are very different. In the no-scale model with non-universal gaugino masses a chargino mass limit of around 100 GeV implies a fine-tuning of between 10 and 20, almost

independently of  $\tan \beta$ , whereas in the conventional no-scale model the corresponding fine-tuning is between 20 and 100.

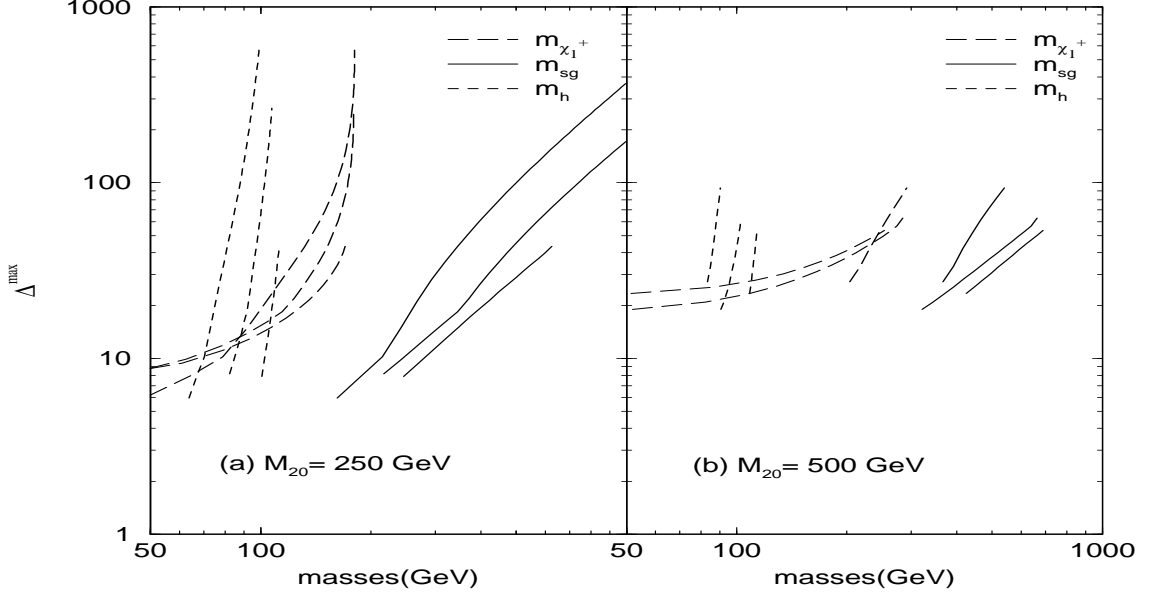


Figure 2: Results for the no-scale with non-universal gaugino masses. The maximum sensitivity parameter  $\Delta^{max}$  is plotted as a function of the lightest CP even Higgs mass (short dashes), gluino mass (solid line) and lightest chargino (long dashes). For each particle type, the three sets of curves correspond to  $\tan \beta = 2, 3, 10$ , from top left to bottom right, respectively. In panel (a) we fix  $M_2(0) = 250$  GeV, while in panel (b)  $M_2(0) = 500$  GeV.

The kinks in the gluino curves in Fig.2(a) correspond to  $\Delta_{M_3(0)}$  being replaced by  $\Delta_{\mu(0)}$  as the largest fine-tuning parameter as  $M_3(0)$  (and thus  $\mu(0)$ ) is increased. For  $M_3(0) < M_2(0)$  a partial cancellation occurs in Eq. (1) between  $M_3(0)$  and  $M_2(0)$  [1], which renders the fine-tuning for  $\mu(0)$  small. Because of that, in the region where the chargino is lighter and mainly higgsino fine-tuning is quite insensitive to its mass. This can be seen clearly in Fig.2(b), where we show results for  $M_2(0) = M_1(0) = 500$  GeV. Interestingly for  $\tan \beta = 3, 10$  the chargino curves are almost flat, due to its Higgsino nature, while for  $\tan \beta = 2$  the curve is much steeper. However, for a chargino mass of order 100 GeV, the overall fine-tuning is larger than in Fig. 2(a). This corresponds to the increase in  $M_3(0)$  when increasing  $M_2(0)$  as required by Eq. (1). For  $\tan \beta = 2$  the curves are cut in the region of a light chargino because the



lightest stop falls below its experimental lower bound<sup>7</sup> of around 90 GeV. For the three values of  $\tan\beta$  considered, an upper limit on  $M_3(0)$  is set by the requirement that the lightest neutralino mass does not exceed the slepton mass.

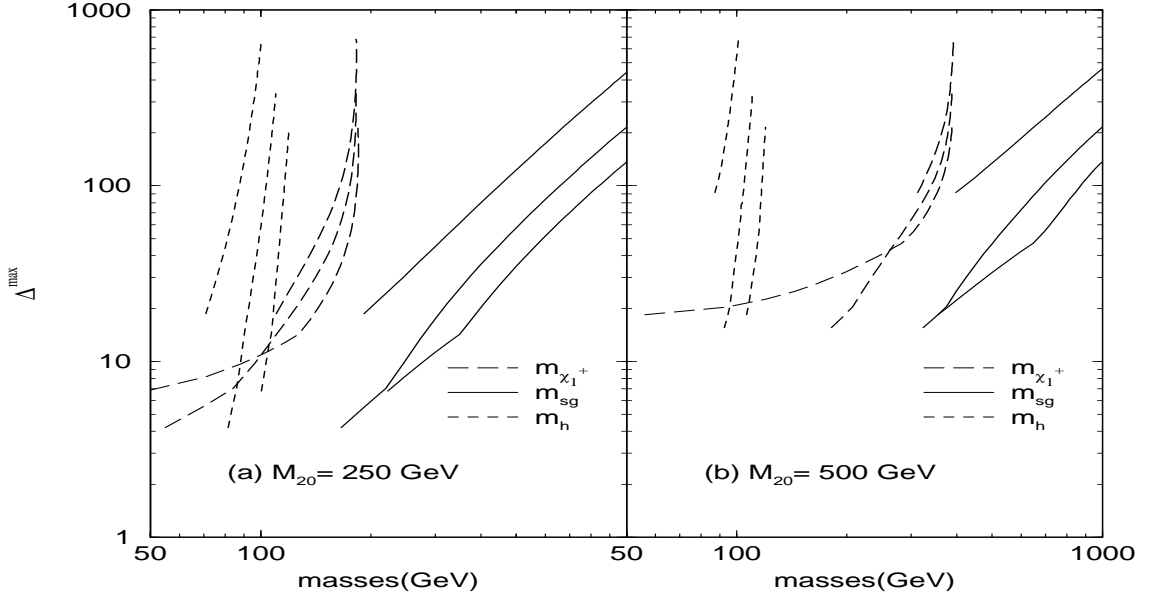


Figure 3: Results for the D-brane model. The maximum sensitivity parameter  $\Delta^{max}$  is plotted as a function of the lightest CP even Higgs mass (short dashes), gluino mass (solid line) and lightest chargino (long dashes). For each particle type, the three sets of curves correspond to  $\tan\beta=2, 3, 10$ , from top left to bottom right, respectively. In panel (a) we fix  $M_2(0) = 250$  GeV, while in panel (b)  $M_2(0) = 500$  GeV.

In Fig.3 we give results for a D-brane scenario, where we take the Goldstino angles  $\cos\theta = 1$  and  $\Theta_3 = 0$ . We also set all the scalar masses equal to the universal value  $m_{5152}^2$  at the high energy scale<sup>8</sup>  $M_U$ . The gaugino masses are again non-universal but now  $M_1(0) = M_3(0)$  and the ratio of these masses to  $M_2(0)$  is controlled by the Goldstino angles  $\Theta_1$  and  $\Theta_2$ . These are constrained to lie along a unit circle, and thus we have only the freedom to change their ratio  $\Theta = \Theta_1/\Theta_2$  when moving along the circumference. Therefore, we compute the fine-tuning for  $\Theta$  instead of those for  $\Theta_1$

<sup>7</sup>The same effect can be seen for the D-brane model in Fig. (3).

<sup>8</sup>Other choices of the Goldstino angles or the scalar masses will affect mainly the low energy values of the scalar masses, and not so much those of the gauginos (a change in  $\cos\theta$  can be compensated by a rescaling of the gravitino mass). This may change the region of the parameter space allowed by the experimental constraints, but it will leave practically unchanged the conclusions on fine-tuning.

and  $\Theta_2$ . The results in Fig.3(a) for  $M_2(0) = 250$  GeV are quite similar to those in Fig.2(a), and imply a similarly low fine-tuning. In Fig.3(b) the choice  $M_2(0) = 250$  GeV now leads to larger allowed regions than in Fig.2(b) due to the presence of a non-zero scalar mass, with the charginos being now significantly heavier due to their gaugino component. Now the parameters that compete to give the largest fine-tuning are  $\mu(0)$  and  $\Theta$ , and the kink in the gluino curves is due to  $\Delta_\Theta$  being replaced by  $\Delta_{\mu(0)}$  as the maximum sensitivity parameter. The other functions  $\Delta_{m_{3/2}}$  and  $\Delta_\theta$  can become comparable but not dominant. As in the generalised no-scale model, the maximum fine-tuning will be insensitive to a light chargino when this is mainly higgsino.

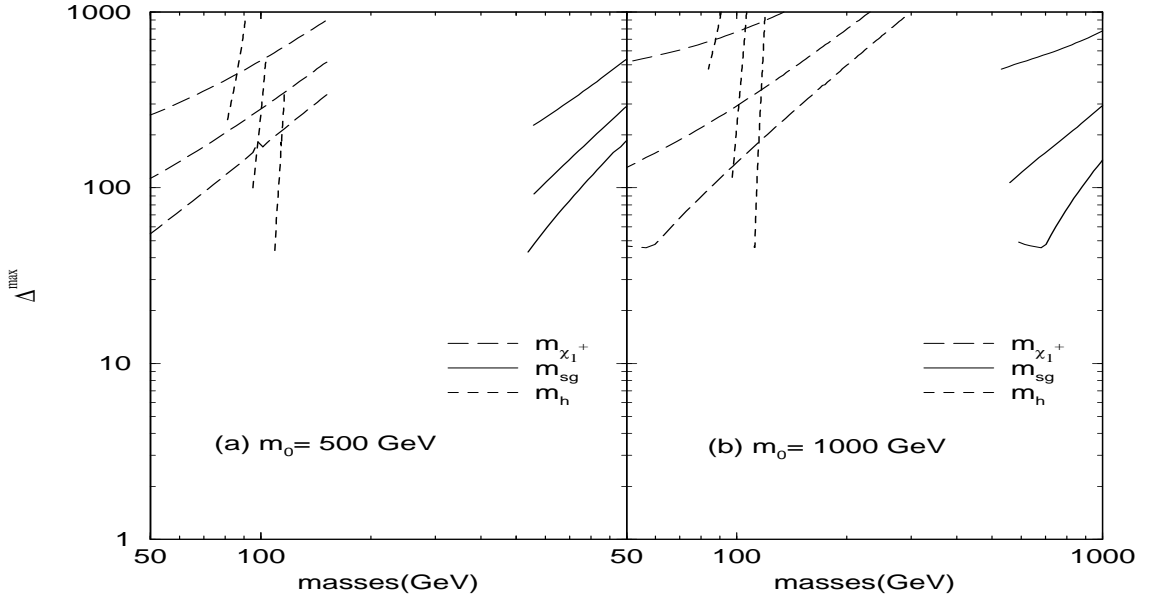


Figure 4: Results for the anomaly mediated supersymmetry breaking model. The maximum sensitivity parameter  $\Delta^{max}$  is plotted as a function of the lightest CP even Higgs mass (short dashes), gluino mass (solid line) and lightest chargino (long dashes). For each particle type, the three sets of curves correspond to  $\tan \beta=2, 3, 10$ , from top left to bottom right, respectively. In panel (a) we fix  $m_0 = 500$  GeV, while in panel (b)  $m_0 = 1000$  GeV.

In Fig.4 we give results for the AMSB model. In the minimal AMSB model where  $m_0 = 0$  the sleptons are predicted to have negative mass squared, so we have followed the common procedure of simply adding a universal scalar mass squared

$m_0^2$  by hand, ensuring that it is large enough to ensure acceptable slepton masses. In Fig.4(a) we choose  $m_0 = 500$  GeV, and in Fig.4(b) we take  $m_0 = 1000$  GeV. In both cases the fine-tuning is dominated by  $\Delta_{\mu(0)}$ , and is much larger than the other models considered. Typically the value of  $\mu(0)$  required by electroweak symmetry breaking is  $O(1 \text{ TeV})$  or larger in this models.

Comparing the results for all the models in Figs.1-4 it is seen that there is slightly less fine-tuning associated with particle masses in the D-brane model than in the other models. However it is also apparent that the results for the no-scale model with non-universal gaugino masses are very similar to the D-brane scenario. The common feature of both these models is non-universal gaugino masses, and the reasons for the reduced fine-tuning are essentially those emphasised in ref.[1] (namely that fine-tuning is most sensitive to  $M_3(0)$  and so  $M_3(0) < M_2(0)$  in general reduces fine-tuning.) However, in the D-brane model there is additionally the possibility of cancellations among different input parameters which help to lower the different fine-tuning parameters. For example, using one-loop semi-analytic solutions to the renormalisation group equations [18] and neglecting one-loop effective potential contributions, we find the approximate expressions for  $\tan \beta = 3$ :

$$\Delta_{m_{3/2}} \approx \tilde{m}_{3/2}^2 \left| \cos^2 \theta (120.67\Theta_1^2 - 8.15\Theta_2^2 + 10.13\Theta_2\Theta_1) - 0.32(1 - 3 \cos \theta^2) \right| \quad (10)$$

$$\begin{aligned} \Delta_{\mu(0)} \approx & \left| 5.12 + \tilde{m}_{3/2}^2 \cos^2 \theta (-135.93\Theta_1^2 + 6.85\Theta_2^2 - 11.40\Theta_2\Theta_1) \right. \\ & \left. + 1.14\tilde{m}_{3/2}^2(1 - 3 \cos^2 \theta) \right|, \end{aligned} \quad (11)$$

$$\Delta_\Theta \approx \tilde{m}_{3/2}^2 \Theta_1 \Theta_2 \left| \cos^2 \theta (128.81\Theta_1 \Theta_2 + 5.07(\Theta_2^2 - \Theta_1^2)) \right|, \quad (12)$$

$$\Delta_\theta \approx \tilde{m}_{3/2}^2 \cos^2 \theta \left| 112.14\Theta_1^2 - 8.15\Theta_2^2 + 8.97\Theta_2\Theta_1 + 0.32 \right|, \quad (13)$$

where  $\tilde{m}_{3/2}$  is the gravitino mass scaled by  $m_Z$ , and we have kept the dependence on  $\cos \theta$  but taken  $\Theta_3 = 0$ . From the above expressions it is clear that choosing appropriate values for the goldstino angles,  $\Delta_{m_{3/2}}$  might be arbitrarily small even for very large values of the gravitino mass, and similarly for  $\Delta_{\mu(0)}$  and  $\Delta_\theta$ .

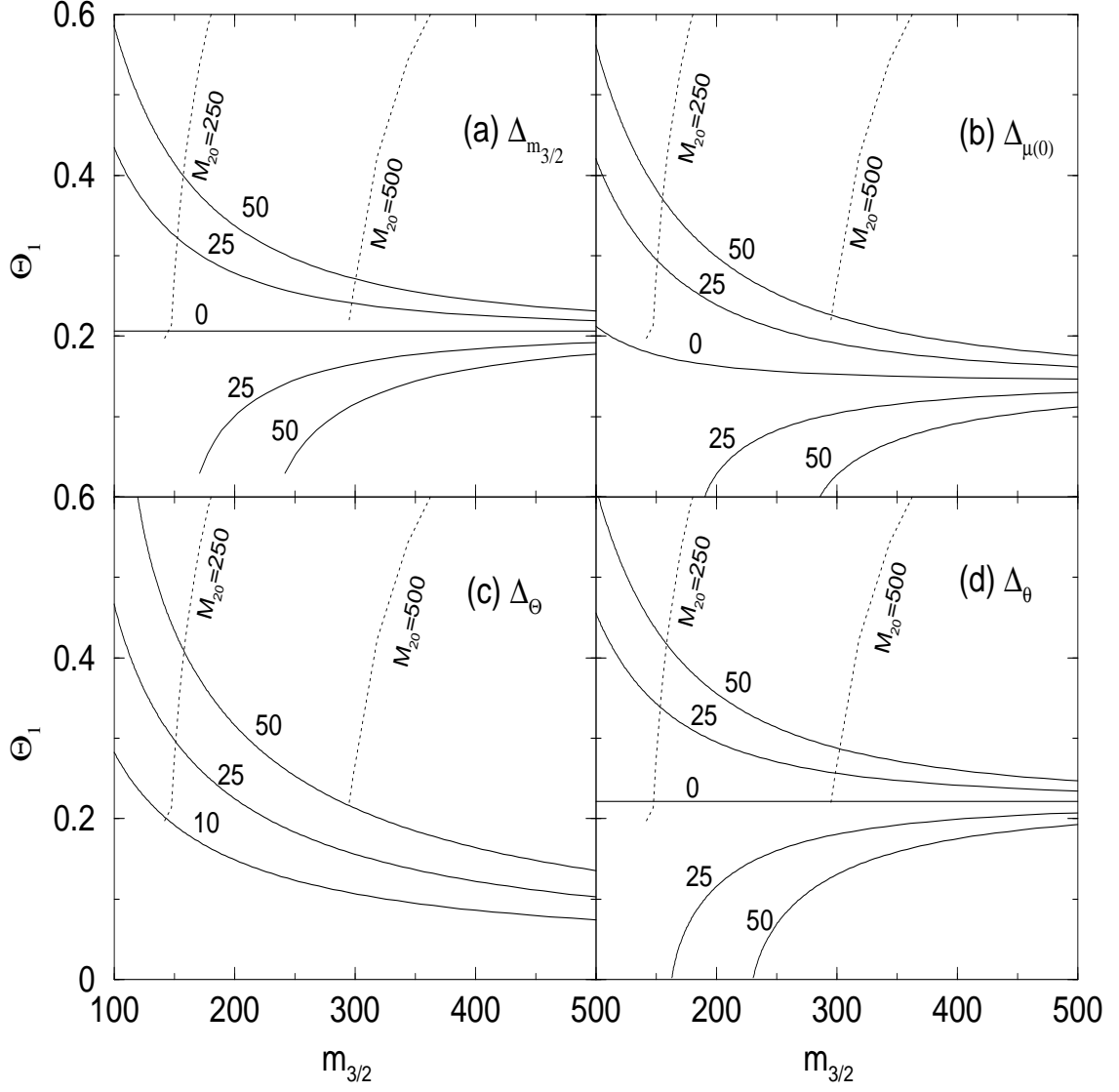


Figure 5: Contours of constant (a)  $\Delta_{m_{3/2}}$ , (b)  $\Delta_{\mu(0)}$ , (c)  $\Delta_{\Theta}$ , and (d)  $\Delta_{\theta}$ , given by the approximate one-loop expressions Eq. (10 - 13), for the D-brane model and  $\tan\beta = 3$ . We have fixed  $\cos\theta = 1$  and  $\Theta_3 = 0$ . The dotted lines are the contours of constant  $M_{20}=250, 500$  GeV.

In Fig. (5) we have plotted the contours of constant  $\Delta_i$  given in Eqs. (10-13). Not suprisingly, all the contours show a hyperbolic behavior: they would more or less follow the curves of constant  $M_3(0)$ , with fine-tuning increasing with the gluino mass. We have also included the contours of constant  $M_2(0)$  for the values considered in Fig. (3). Although  $\Delta_{\mu(0)}$ ,  $\Delta_{m_{3/2}}$  and  $\Delta_{\theta}$  are all simultaneously small for  $\Theta_1 \simeq 0.2$ , parts of this region are experimentally excluded due to  $\mu$  becoming too small and hence

the lightest chargino becoming too light. Nevertheless, there are allowed regions in the plane  $m_{3/2} - \Theta_i$ , corresponding to a light gluino, where  $\Delta_{\mu(0)}$ ,  $\Delta_{m_{3/2}}$  and  $\Delta_\theta$  are all simultaneously small, and the maximum sensitivity would be given by  $\Delta_\Theta$ . We may try to play with the values of either  $\cos\theta$  or  $\Theta_3$  in order to find some region where *all* the fine-tuning is small. However, reducing (increasing)  $\cos\theta$  ( $\Theta_3$ ) the slepton masses tend to diminish, making it difficult if not impossible to fulfill the experimental constraints on the SUSY masses<sup>9</sup>.

Any conclusions which are drawn from fine-tuning are always subject to caveats, disclaimers and health warnings. A precise value cannot be placed on fine-tuning, since the definition can always be changed and the question of how much fine-tuning is acceptable is subjective. For this reason we prefer not to give upper bounds on particle masses based on fine-tuning, but clearly subjective upper bounds can be read off from our curves, for those inclined to do so. The main value of our work is to compare different SUGRA models with each other, and within each SUGRA model to compare different regions of parameter space, from the point of view of fine-tuning.

In all models, fine-tuning is reduced as  $\tan\beta$  is increased, with  $\tan\beta = 10$  preferred over  $\tan\beta = 2, 3$ . Nevertheless, the present LEP2 limit on the Higgs and chargino mass of about 100 GeV and the gluino mass limit of about 250 GeV implies that  $\Delta^{max}$  is of order 10 or higher. The fine-tuning increases most sharply with the Higgs mass. The Higgs fine-tuning curves are fairly model independent, and as the Higgs mass limit rises above 100 GeV come to quickly dominate the fine-tuning. We conclude that the prospects for the discovery of the Higgs boson at LEP2 are good. For each model there is a correlation between the Higgs, chargino and gluino mass, for a given value of fine-tuning. For example if the Higgs is discovered at a particular mass value, then the corresponding chargino and gluino mass for each  $\tan\beta$  can be read off from

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<sup>9</sup>For example, for  $\cos\theta < 0.5$  and  $\tan\beta > 3$ , the parameter space compatible with experiments shrinks to nothing.

Figs.1-4.

The new general features of the results may then be summarised as follows:

- The gluino mass curves are less model dependent than the chargino curves, and this implies that in all models if the fine-tuning is not too large then the prospects for the discovery of the gluino at the Tevatron are good.
- The fine-tuning due to the chargino mass is model dependent. For example in the no-scale model with non-universal gaugino masses and the D-brane scenario the charginos may be relatively heavy compared to mSUGRA.
- Some models have less fine-tuning than others. We may order the models on the basis of fine-tuning from the lowest fine-tuning to the highest fine-tuning: D-brane scenario < generalised no-scale SUGRA < mSUGRA < AMSB.
- The D-brane model is less fine-tuned partly because the gaugino masses are non-universal, and partly because there are large regions where  $\Delta_{m_{3/2}}$ ,  $\Delta_{\mu(0)}$ , and  $\Delta_\theta$  are all close to zero (see Fig.5). However in these regions the fine tuning is dominated by  $\Delta_\Theta$ , and this leads to an inescapable fine-tuning constraint on the Higgs and gluino mass.

Finally we should comment on the parameter space dependence of our results. Although the results presented here are for specific choices of parameters, we have performed a detailed analysis of the parameter space of these models and found that the results are representative of the full parameter space, and the qualitative conclusions will not change. We shall present the complete analysis elsewhere [19].

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## References

- [1] G. L. Kane and S. F. King, Phys. Lett. **B 451** (1999) 113, hep-ph/9810374.
- [2] J. L. Feng, K. T. Matchev, T. Moroi, hep-ph/9909334; J. L. Feng, K. T. Matchev, T. Moroi, hep-ph/9908309.
- [3] S. Dimopoulos and G.-F. Giudice, Phys. Lett. **B 357** (1995) 573.
- [4] J. Ellis, K. Enqvist, D. Nanopoulos and F. Zwirner, Nucl. Phys. **B 276** (1986) 14; R. Barbieri and G.-F. Giudice, Nucl. Phys. **B 306** (1988) 63; G. G. Ross and R. G. Roberts, Nucl. Phys. **377** (1992) 571; B. de Carlos and A. Casas, Phys. Lett. **309** (1993) 320; A. Pomarol and D. Tommasini, Nucl. Phys. **466** (1996) 3; G. W. Anderson and D. J. Castano, Phys. Lett. **B 347** (1995) 300; G. W. Anderson and D. J. Castano, Phys. Rev. **D 52** (1995) 1693; G. W. Anderson and D. J. Castano, Phys. Rev. **D 53** (1996) 2403; G. W. Anderson, D. J. Castano and A. Riotto, Phys. Rev. **D 55** (1997) 2950.
- [5] P. Chankowski, J. Ellis and S. Pokorski, Phys. Lett. **B 423** (1998) 327; R. Barbieri and A. Strumia, Phys. Lett. **B 433** (1998) 63; P. Chankowski, J. Ellis, M. Olechowski and S. Pokorski, hep-ph/9808275; Kwok Lung Chan, Utpal Chattopadhyay, and Pran Nath, Phys. Rev. **58** (1998) 096004.
- [6] D. Wright, hep-ph/9801449, UW/PT-97/27.
- [7] For a review see A. B. Lahanas and D. V. Nanopoulos, Phys. Rep. **145** (1987) 1; J. L. Lopez and D. V. Nanopoulos, Int. J. Mod. Phys. **A11** (1996) 3439.
- [8] L. E. Ibañez, C. Muñoz and S. Rigolin, hep-ph/9812397; M. Brhlik, L. Everett, G. Kane and J. Lykken, hep-ph/9905215.
- [9] L. Randall and R. Sundrum, hep-th/9810155; G. Giudice, M. Luty, H. Murayama and R. Rattazzi, JHEP **9812** (1998) 027; J. L. Feng, T. Moroi, L. Randall, M.

- Strassler and S. Su, hep-ph/9904250; T. Gherghetta, G. Giudice and J. Wells, hep-ph/9904378.
- [10] S. P. Martin and M. T. Vaughn, Phys. Rev. **D50** (1994) 2282; I. Jack and D. R. T. Jones, Phys. Lett. **B333** (1994) 374; Y. Yamada, Phys. Rev. **D50** (1994) 3537; I. Jack, D. R. T. Jones, S. P. Martin, M. T. Vaughn and Y. Yamada, Phys. Rev. **D50** (1994) 5481.
  - [11] A. E. Faraggi and B. Grinstein, Nucl. Phys. **422** (1994) 3; P. Chankowski, Z. Pluciennik and S. Pokorski, Nucl. Phys. **439** (1995) 23; M. Bastero-Gil and J. Pérez-Mercader, Nucl. Phys. **B450**, 21 (1995); J. Bagger, K. Matchev and D. Pierce, Phys. Lett. **348** (1995) 443.
  - [12] D. M. Pierce, J. A. Bagger, K. Matchev, Ren-jie Zhang Nucl. Phys. **B 491** (1997) 3.
  - [13] S. Coleman and E. Weinberg, Phys. Rev. **7** (1973) 1888; S. Weinberg, Phys. Rev. **7** (1973) 2887.
  - [14] G. Gamberini, G. Ridolfi and F. Zwirner, Nucl. Phys. **B331** (1990) 331; R. Arnowitt and P. Nath, Phys. Rev. **D46** (1992) 3981.
  - [15] J. Casas, J. Espinosa, M. Quirós and A. Riotto, Nucl. Phys. **B436** (1995) 3, Erratum:*ibid.* **439** (1995) 466; M. Carena, J. Espinosa, M. Quirós and C. Wagner, Phys. Lett. **B355**(1995) 209; M. Carena, M. Quirós and C. Wagner, Nucl. Phys. **B461** (1995) 407; H. Haber, R. Hempfling and A. Hoang, Z. Phys. **C75** (1997) 539.
  - [16] S. Heinemeyer, W. Hollik and G. Weiglein, Phys. Rev. **D58** (1998) 091701; Phys. Lett. **B440** (1998) 296; Eur. Phys. Jour. **C9** (1999) 343.
  - [17] S. P. Martin, M. T. Vaughn, Phys. Lett. **B 318** (1993) 331;



- [18] M. Carena, P. Chankowski, M. Olechowski, S. Pokorski and C. E. M. Wagner,  
Nucl. Phys. **B491** (1997) 103.
- [19] M. Bastero-Gil, S.F. King and G.L. Kane (to appear).